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Stability of the film flow passing round the cross-section elements in the area of high density irrigation

S E Shcheklein¹ and E M Bochkareva²

¹ Ural Federal University, Department of Nuclear Power Plants and Renewable Energy Sources, 620002 Yekaterinburg, st. Mira 19, Russia

² Kutateladze Institute of Thermophysics, 630090 Novosibirsk, 1 Acad. Lavrentiev ave., Russia

E-mail: s.e.shcheklein@urfu.ru

Abstract. The paper studies the loss of stability of a liquid film using regular surface roughness. The model of the breakdown process is described and the conditions for the formation of a liquid film breakdown are determined experimentally. It was found that there are two characteristic modes, namely drop and film regimes. Using the methods of thermal anemometry, data were obtained on the distribution of the droplet sizes after a film breakdown and the dependence of the We number on the projection arrangement height was plotted.

1. Introduction

In studies of the heat exchange enhancement in a liquid film by a surface with regular transverse roughness, the effect of loss of film flow stability with partial or complete destruction of the film was observed, as a result of the appearance of a drop or film breakdown of the liquid [1].

Previously, systematic studies of fluid stripping during the free flow of films along smooth surfaces were performed in [2], where it was shown that the breakdown occurs only for large Re film numbers (10^4) and a path length of about 10 m; the authors of paper [3] investigated the liquid breakdown during the cocurrent flow of the film and the gas flow.

However, the search of new methods for intensifying heat transfer in film flows using elements of roughness, surface coiling, finning, knurling, and surface profiling can result not only in the expected increase in heat transfer due to fluid turbulence and growth of the heat exchange surface, but also undesirable effects of stability loss of the film with a much earlier destruction.

2. Process model

When the liquid film flows through surfaces with regular transverse roughness, an additional force, normal to the surface, arises due to the braking and flowing around the roughness element by film. Assuming that the kinetic energy of the flow during the braking of liquid is expended on the curvature of the film surface and the projection formation, a part of the liquid can be torn off the film surface at that moment. The factor of breakdown in this case is conditioned by the inequality:

$$E_k > A_\sigma, \quad (1)$$

where A_σ is a work of surface tension forces.



The problem reduces to determining the mass of a liquid whose kinetic energy is spent on the formation of a projection sufficient to form a drop of critical size.

For $h < r$, the mass of the stopping fluid can be estimated as:

$$m = \int_0^t \rho h u l dt \cong \rho h l (r - h), \quad (2)$$

where h is the average film thickness, u is the average film speed, $(r - h)$ is the braking length, r is the protrusion height, l is the unit width, ρ is the fluid density, t is the breaking time.

From equation (2) it follows that:

$$E_k = \rho h l (r - h) \frac{u^2}{2}. \quad (3)$$

The work of surface tension forces:

$$A_\sigma = \int_0^S \sigma dt = \pi \sigma d^3 l, \quad (4)$$

where d_{eq} is the equivalent droplet diameter, S is the droplet surface area, σ is the coefficient of surface tension of liquid.

Equating (2) and (4), we obtain an expression relating the flow and roughness characteristics, corresponding to the origin of liquid breakdown from the surface of the film in the form of drops:

$$r = \frac{2\pi\sigma d^3}{\rho h u^2} + h = \frac{8\pi d^3}{We} + h, \quad (5)$$

where $We = \rho h u^2 \sigma^{-1}$ is the Weber number.

To determine d_{eq} , an experimental detection of the fluid breakdown formation conditions on a single roughness and the droplet size spectra was performed.

3. Experimental procedure

The experiment was carried out on a cylindrical channel with a diameter of 60 mm and a length of 2 m included in the water circulation circuit within the range of irrigation densities from 0.1 to 2.5 kg/m²s, which corresponds under normal conditions to the range of Reynolds numbers for the film of 250 – 10⁴.

At the hydrodynamically stabilized section of the film flow (1.5 m), single rings of circular cross section of various diameters (heights) were installed. The height of the rings ranged from 0.1 mm to 3 m, i.e. from $(r < h)$ to $(r > h)$. The appearance of the breakdown was detected visually. For the drop breakdown conditions, the flow rate of liquid remaining on the channel surface was fixed in a dimensional way. The size distribution of droplets was determined using a modified temperature constant anemometer method. To exclude the deposition of liquid on the filament, its temperature was above the Leidenfrost temperature. The thread of the thermo-anemometer was installed in a section (in the radial direction) corresponding to the maximum density of the droplet flow. At the same time, the flow rate of the liquid was measured with the sampler unit in the same section. The number and duration of pulses that occurred as a result of droplets falling onto the thread were fixed by means of the recording instrument.

It is found that there are two drop and film breakdown specific regimes. The first is a set of small droplets. The second is the complete separation of the film from the surface and the appearance of a free spatial film structure (in the form of an umbrella). Typical schemes for the formation of disruptive phenomena in the flow around an obstacle by film are shown in figure 1.

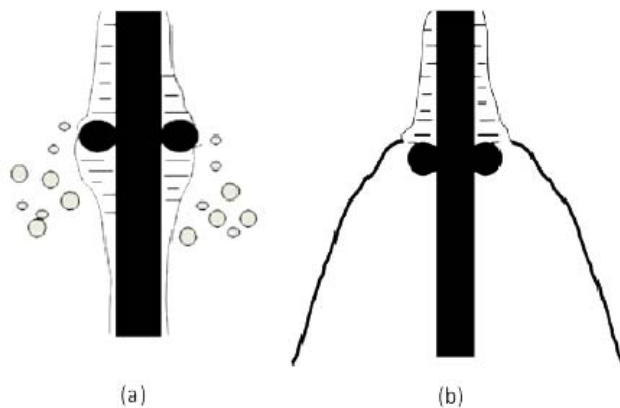


Figure 1. Schemes of the formation of fluid breakdown during film flow around a transverse obstacle. (a) – drop breakdown; (b) – film breakdown.

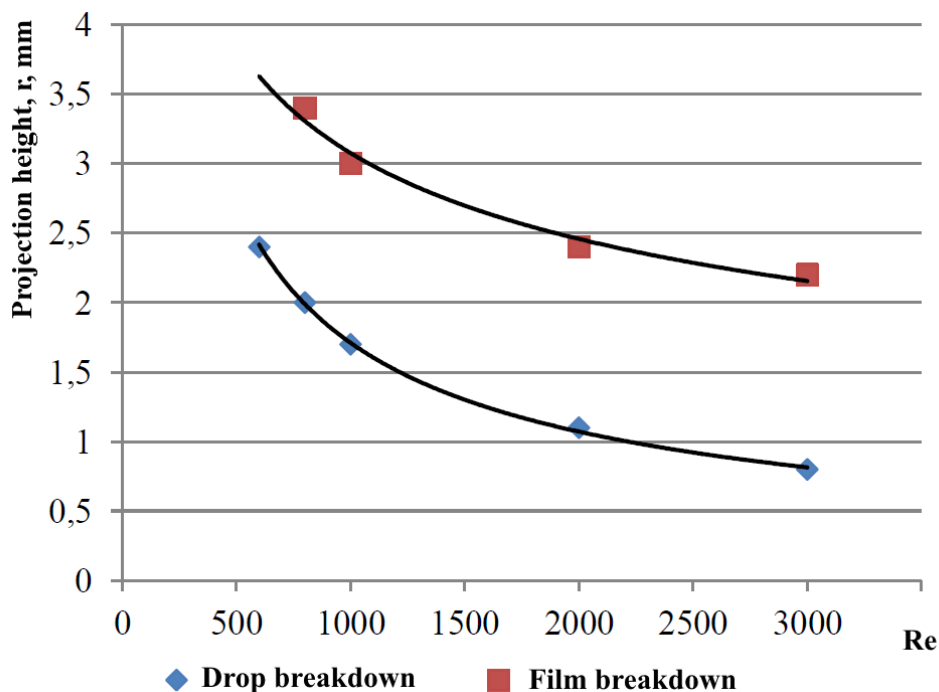


Figure 2. Diagram of the boundaries of the origin of fluid breakdown.

With an increase in the liquid flow rate in the film, the size and number of droplets increases with the formation of a continuous film breakdown. The results of the experimental determination of the disruption regimes boundaries are shown in figure 2.

4. Methods of processing the results

To determine the equivalent size of disrupting drops of liquid d_{eq} , the methods of thermoanemometry of the sampler were used.

Since the transfer of liquid into the sampler occurred only due to droplet moisture; under the assumption that the droplets are spherical for a known flow in the cross section, the most probable pulse duration can be related with droplet diameter by the relation:

$$\langle d \rangle \approx 2 \left(\frac{G_{av} \langle T \rangle}{0.75h} \right)^{1/3}. \quad (6)$$

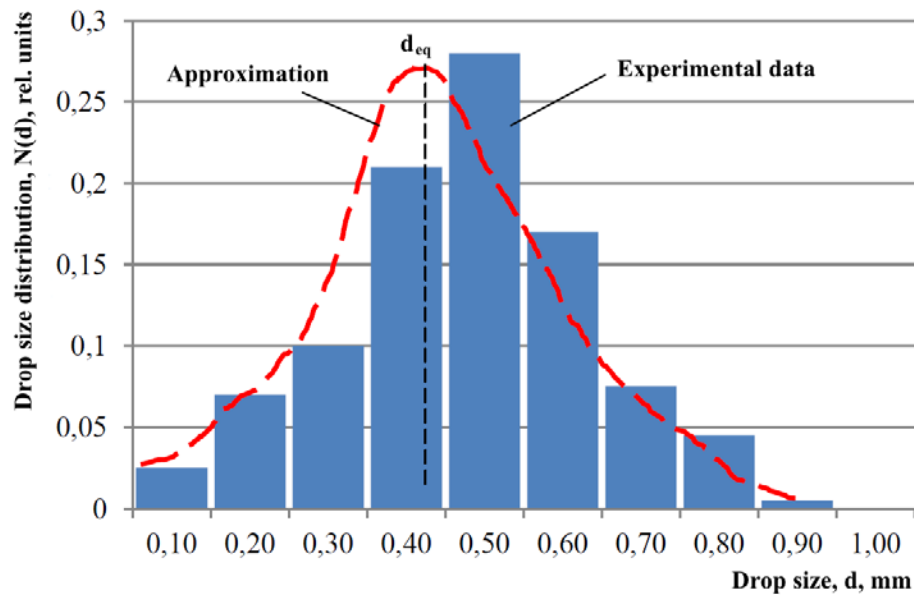


Figure 3. Distribution of the breakdown droplets in size.

The experimentally obtained density of the touch periods distribution according to the equation (6) is transformed to the density of dimensions and is shown in figure 3 for rings giving the maximum intensity of a breakdown.

It is obvious that the droplet size distribution is very close to the normal distribution law. The modal drop size $\langle d \rangle$ on the curve in figure 3 is equal to 0.45 mm. Substitution of the value $\langle d \rangle$ in equation (5) as an equivalent allows obtaining a relation connecting the roughness with the regime parameters:

$$r = \frac{11,3}{We_{cr}} + h, \quad (7)$$

where We_{cr} is critical Weber number corresponding to the origin of drop breakdown of liquid. The results of the calculation of equation (7) using the dependences [4] for determining u and h are shown in figure 4.

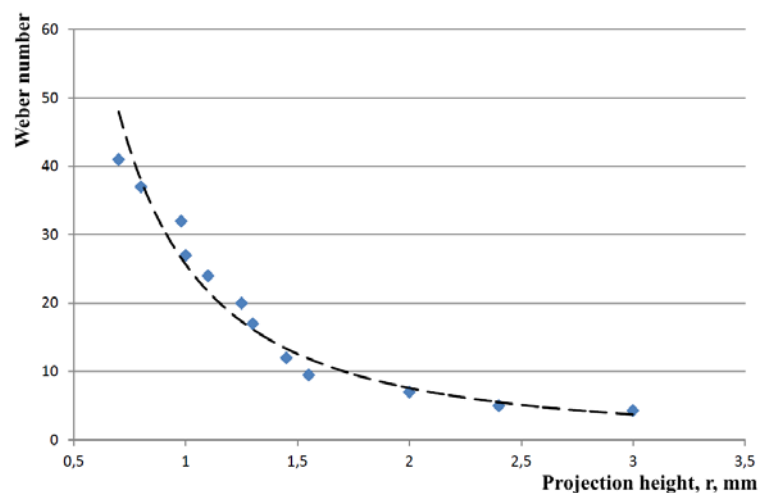


Figure 4. Dependence of the Weber number on the projection height for determining the origin of the drop breakdown with free liquid film flow.

In gas-film systems, one should also expect a breakdown at lower liquid flow rates and gas (vapor) velocities for a flow over rough surfaces than that for smooth surfaces due to the force exerted by the steam on the condensate film.

5. Conclusions

1. Conditions conducive to the acceleration of drop breakdown are created for free flow of the liquid film along the surface with transverse nonuniformity of surface windings, finning, knurling (profiling of the surfaces),.
2. At high irrigation densities and nonuniformity, height commensurate with the thickness of the film, and thus a continuous film breakdown of the liquid appears in the form of a spatial film. The surface of the channel after the nonuniformity ceases to be wetted by the liquid.
3. These effects should be taken into account when developing methods for intensifying heat transfer from the surface, or used to remove a film that interferes with high heat transfer (film condensation of steam).

Acknowledgments

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